CS 105

"Tour of the Black Holes of Computing"

File Systems

Topics

- Design criteria
- History of file systems
- Berkeley Fast File System
- Effect of file systems on programs

File Systems: Disk Organization

A disk is a sequence of 4096-byte *sectors* or *blocks*

- Can only read or write in block-sized units

First comes *boot block* and *partition table*

Partition table divides the rest of disk into partitions

- May appear to operating system as logical "disks"
- Useful for multiple OSes, etc.
- Otherwise bad idea; hangover from earlier days

File system: partition structured to hold *files* (of data)

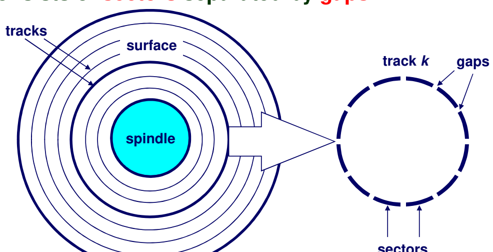
- May aggregate blocks into *segments* or *clusters*
  - Typical size: 8K–128M bytes
  - Increases efficiency by reducing overhead
  - But may waste space if files are small

Disk Geometry

Disks consist of stacked platters, each with two surfaces

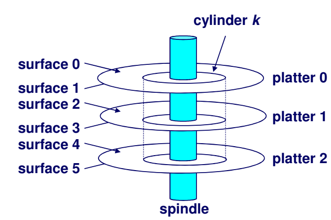
Each surface consists of concentric rings called tracks

Each track consists of sectors separated by gaps

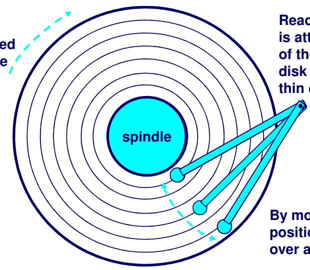


Disk Geometry (Muliple-Platter View)

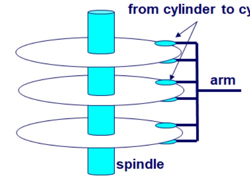
Aligned tracks form a cylinder (this view is outdated)



Disk Operation (Single-Platter View)



Disk Operation (Multi-Platter View)



Disk Access Time

Average time to access some target sector approximated by :

- $T_{access} = T_{avg\ seek} + T_{avg\ rotation} + T_{avg\ transfer}$

Seek time ($T_{avg\ seek}$)

- Time to position heads over cylinder containing target sector
- Typical $T_{avg\ seek}$ = 9 ms

Rotational latency ($T_{avg\ rotation}$)

- Time waiting for first bit of target sector to pass under read/write head
- $T_{avg\ rotation}$ = 1/2 x 1/RPMs x 60 sec/1 min

Transfer time ($T_{avg\ transfer}$)

- Time to read the bits in the target sector.
- $T_{avg\ transfer}$ = 1/RPM x 1/(avg # sectors/track) x 60 secs/1 min

Disk Access Time Example

Given:

- Rotational rate = 7200 RPM (typical desktop; laptops usually 5400)
- Average seek time = 9 ms (given by manufacturer)
- Avg # sectors/track = 400

Derived:

- $T_{avg\ rotation}$ = 1/2 x (60 secs/7200 RPM) x 1000 ms/sec = 4 ms
- $T_{avg\ transfer}$ = 60/7200 RPM x 1/400 secs/track x 1000 ms/sec = 0.02 ms
- T_{access} = 9 ms + 4 ms + 0.02 ms

Important points:

- Access time dominated by seek time and rotational latency
- First bit in a sector is the most expensive, the rest are "free"
- SRAM access time is about 4 ns/doubleword, DRAM about 60 ns
  - Disk is about 40,000 times slower than SRAM, and
  - 2,500 times slower then DRAM

Logical Disk Blocks

Modern disks present a simpler abstract view of the complex sector geometry:

- Set of available sectors is modeled as a sequence of b-sized logical blocks (0, 1, 2, ...)

Mapping between logical blocks and actual (physical) sectors

- Maintained by hardware/firmware device called *disk controller* (partly on motherboard, mostly in disk itself)
- Converts requests for logical blocks into (surface,track,sector) triples

Allows controller to set aside spare cylinders for each zone

- Accounts for (some of) the difference in "formatted capacity" and "maximum capacity"

Block Access

Disks can only read and write complete sectors (blocks)

- Not possible to work with individual bytes (or words or…)
- File system data structures are usually smaller than a block
- OS must pack structures together to create a block

Disk treats all data as uninterpreted bytes (one block at a time)

- OS must read block into (byte) buffer and then convert into meaningful data structures
- Conversion process is called *serialization* (for write) and *deserialization*
- OS carefully arranges for this to happen by simple C type-casting

Need to work in units of blocks affects file system design

- Writing (e.g.) a new file name inherently rewrites other data in same block
- But block writes are atomic ➔ can update multiple values at once

Aside: Solid-State Disks

They aren't disks! But for backwards compatibility they pretend to be…

SSDs are divided into *erase blocks* made up of *pages*

- Typical page: 4K-8K bytes
- Typical erase block: 128K-512K

Can only change bits from 1 to 0 when writing

- Erase sets entire block to all 1's
- Erase is slow
- Can only erase 10^4 to 10^6 times
- Must pre-plan erases and manage wear-out

Net result:

- Reads are fast (and almost truly random-access)
- Writes are 100X slower (and have weird side effects)

Design Problems

So, disks have mechanical delays (and SSDs have their own strange behaviors)

Fundamental problem in file-system design: how to hide (or at least minimize) these delays?

Side problems also critical:

- Making things reliable (in face of software and hardware failures)
  - People frown on losing data
- Organizing data (e.g., in directories or databases)
  - Not finding stuff is almost as bad as losing it
- Enforcing security
  - System should only share what you *want* to share

Typical Similarities Among File Systems

A (secondary) boot record

A top-level directory

Support for hierarchical directories

Management of free and used space

Metadata about files (e.g., creation date)

Protection and security

Typical Differences Between File Systems

Naming conventions: case, length, special symbols

File size and placement

Speed

Error recovery

Metadata details

Support for special files

Snapshot support

Case Study: Berkeley Fast File System (FFS)

First public Unix (Unix V7) introduced many important concepts in Unix File System (UFS)

- I-nodes
- Indirect blocks
- Unix directory structure and permissions system

UFS was simple, elegant, and slow

Berkeley initiated project to solve the slowness

Many modern file systems are direct or indirect descendants of FFS

- In particular, EXT2 through EXT4

FFS Headers

Boot block: first few sectors

- Typically all of cylinder 0 is reserved for boot blocks, partition tables, etc.

Superblock: file system parameters, including

- Size of partition (note that this is dangerously redundant)
- Location of root directory
- Block size

Cylinder groups, each including

- Data blocks
- List of *inodes*
- Bitmap of used blocks and fragments in the group
- Replica of superblock (not always at start of group)

FFS File Tracking

Directory: file containing variable-length records

- File name
- Inode number

Inode: holds metadata for one file

- Fixed size
- Located by number, using information from superblock (basically, array)
- Integral number of inodes in a block
- Includes
  - Owner and group
  - File type (regular, directory, pipe, symbolic link, …)
  - Access permissions
  - Time of last i-node change, last modification, last access
  - Number of links (reference count)
  - Size of file (for directories and regular files)
  - Pointers to data blocks
- Except for pointers, precisely what's in `stat` data structure

FFS Inodes

Inode has 15 pointers to data blocks

- 12 point directly to data blocks
- 13th points to an *indirect block*, containing pointers to data blocks
- 14th points to a *double* indirect block
- 15th points to a *triple* indirect block

With 4K blocks and 4-byte pointers, the triple indirect block can address 4 terabytes (2^{42} bytes) in one file

Data blocks might not be contiguous on disk

But OS tries to *cluster* related items in cylinder group:

- Directory entries
- Corresponding inodes
- Their data blocks

FFS Free-Space Management

Free space managed by bitmaps

- One bit per block
- Makes it easy to find groups of contiguous blocks

Each cylinder group has own bitmap

- Can find blocks that are physically nearby
- Prevents long scans on full disks

Prefer to allocate block in cylinder group of last previous block

- If can't, pick group that has most space
- Heuristic tries to maximize number of blocks close to each other

Effect of File Systems on Programs

Software can take advantage of FFS design

- Small files are cheap: spread data across many files
- Directories are cheap: use as key/value database where file name is the key
  - But only if value (data) is fairly large, since size increment is 4K units
- Large files well supported: don't worry about file-size limits
- Random access adds little overhead: OK to store database inside large file
  - But don't forget you're still paying for disk latencies and indirect blocks!

FFS design also suggests optimizations

- Put related files in single directory
- Keep directories relatively small
- Recognize that single large file will eat much remaining free space in cylinder group
  - Create small files before large ones

The Crash Problem

File system data structures are interrelated

- Free map implies which blocks do/don't have data
- Inodes and indirect blocks list data blocks
- Directories imply which inodes are allocated or free
- All live in different places on disk
- Which to update first?

Crash in between updates means inconsistencies

- Block listed as free but really allocated will get reused
- Block listed as allocated but really free means space leak
- Allocated inode without directory listing means lost file

File System Checking

Traditional solution: verify all structures after a crash

- Look through files to find out what blocks are in use
- Look through directories to find used inodes
- Fix all inconsistencies, put lost files in "`lost+found`"

Problem: takes a long time

- Following directory tree means random access
- Following indirect blocks is also random
- Random == slow
- Huge modern disks ⇒ hours or even days to verify
  - System can't be used during check

Journaled File Systems

One (not only) solution to checking problem

- Before making change, write intentions to journal
  - "I plan to allocate block 42, give it to inode 47, put that in directory entry foo"
  - Journal writes are carefully kept in single block ⇒ atomic
- After making changes, append "I'm done" to journal

Post-crash journal recovery

- Journal is sequential and fairly small ⇒ fast scanning
- Search for last "I'm done" record
- Re-apply any changes past that point
  - Atomicity means they can't be partial
  - All changes are arranged to be idempotent
- Write an "I'm done" in case of another crash

Summary: Goals of Unix File Systems

Simple data model

- Hierarchical directory tree
- Uninterpreted (by OS) sequences of bytes
- Extensions are just strings in long filename

Multiuser protection model

High speed

- Reduce disk latencies by careful layout
- Hide latencies with caching
- Amortize overhead with large transfers
- Sometimes trade off reliability for speed